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SCIENCE

Snæfellsjökull volcano-centred ice cap landsystem, West Iceland

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ABSTRACT

A 1:10,526 scale map of Snæfellsjökull and its forelands is presented as the first landsystem exemplar of volcano-centred ice caps, for application to understanding glacierized volcanic terrains globally. Mapping of surface materials and landforms was undertaken using orthorectified aerial photographs taken in 2002 and results of ground truth fieldwork in 2010. Nine natural surficial geology units were identified in addition to bedrock, glacier ice and made ground associated with pumice mining. The spatial distribution of landforms and sediments throughout the forelands comprises extensive areas of ice-cored moraine, developed at the limit of the Little Ice Age readvance and located distal to extensive areas of fluted till and glacially abraded bedrock with occasional eskers. This is a widely recognized landsystem signature typical of former polythermal snout conditions at the Little Ice Age maximum. Proglacially, thrust pumice sheets also occur on the east flanks of the volcano where pre-existing deformable materials were susceptible to thrust block development.

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1. Introduction

Snæfellsjökull is typical of the many small mountain-centred icefields and ice caps in Iceland and indeed the North Atlantic region in that it is rapidly thinning and receding from its historical Little Ice Age maximum limit, having profound effects on the generation of freshwater for surrounding communities. Emerging on the forelands of these Icelandic mountain glaciers are landform-sediment assemblages that represent the process-form relationships (landsystems) of upland cryosphere settings as well as records of changing glacier dynamics triggered by recent climate change. Mapping these forelands has facilitated a greater understanding of the range of upland icefield landsystems and their dynamics, specifically at, and since, the Little Ice Age. To date, Icelandic upland landsystem models or exemplars have related to plateau icefield settings (e.g. Brynjólfsson, Schomacker, & Ingólfsson, 2014; Evans, 2010; Evans, Twigg, & Shand, 2006, 2015a) and cirque glaciers (Brynjólfsson, Ingólfsson, & Schomacker, 2013) but volcano-centred ice cap landsystems have not been assessed in a holistic way. A 1:10,526 scale map (Main Map) of Snæfellsjökull is presented here as the first landsystem exemplar of volcano-centred ice caps, relevant specifically to the Icelandic landscape but also more widely to glacierized volcanic terrains globally.

2. Study area and methods

Snæfellsjökull (64°48'N, 23°47'W) is located in western Iceland, on the westernmost tip of the Snæfellsnes

Peninsula (Figure 1) and became known as the fictional route to the underworld after Jules Verne's 1864 novel *Journey to the centre of the earth*. The multi-lobed ice cap covers an area of almost 12.5 km². It occupies the summit and fills the caldera of an active stratovolcano that reaches a maximum elevation of 1446 m above sea level (Thordarson & Larsen, 2007). The volcano is a stratovolcano-tuya hybrid formed in the trans-current fault-zone of the North Atlantic spreading ridge (Hards, Kempton, Thompson, & Greenwood, 2000; Thordarson & Larsen, 2007). The highly variable volcanic conditions associated with this hybrid feature makes the geology of the area relatively complex (Figure 2), characterized by a suite of mildly alkali basalts and peralkaline rhyolites that are geochemically similar to those from the Icelandic Torfajökull volcano (Hards et al., 2000; MacDonald, McGarvie, Pinkerton, Smith, & Palacz, 1990). Volcanic activity over the last 0.7–0.8 Ma is represented by early-, late- and post-glacial stages of landform development (Hardarson & Fitton, 1991; Kristjánsson, Johannesson, Eiríksson, & Guðmundsson, 1988) but the majority of the Snæfellsjökull volcano is covered by post-glacial lava flows that are less than 10,000 years old (Figure 2(b)), even though the oldest dated rocks date back to 842 ka (Jóhannesson, Flores, & Jonsson, 1981; Kokfelt, Hoernle, Lundstrom, Hauff, & van den Bogaard, 2009). Three large post-glacial tephra deposits have been radiocarbon dated to 7–9 ka BP, 3960 and 1750 years BP (Steinþorsson, 1967). Very prominent in this respect is the blanket of light brown pumice and tephra that lies on the outer forelands of the eastern and northeastern margins of the ice cap, a deposit



Figure 1. Aerial view of Snæfellsjökull from the south, taken on 18 October 2001. Source: Oddur Sigurðsson.

that was extensively mined during the twentieth century. Elsewhere the steep volcano flanks are characterized by several subsidiary craters and impressive lava flows, which are partially depicted by the orthophoto component of the [Main Map](#).

Given its altitude and proximity to the North Atlantic Ocean moisture source, Snæfellsjökull likely develops as a summit ice cap in between periods of intensive volcanic activity when climate conditions are at least comparable with those of the Little Ice Age; as the ice cap is presently in a state of rapid recession, its present day existence might be entirely related to the climate conditions of the Little Ice Age, during which it expanded to around 22 km² in area. However it is not possible to determine whether or not present day climate warming will remove what has been a stable summit ice cap for the first time in the Holocene epoch. The maximum extent of the most recent, historical glacier advance is demarcated by prominent moraines on the forelands of the five named outlet lobes of the ice cap, including Kvíahnúksjökull to the south, Hólatindajökull to the southwest, Blágilsjökull to the north, and Jökulhálsjökull and Hyrningsjökull on the northeast margin ([Main Map](#)). However, the exact age of this advance is unknown and therefore can be related only to the broader definition of the Little Ice Age in the context of the observations made by [Matthews and Briffa \(2005\)](#) and [Kirkbride and Dugmore \(2006\)](#). Firstly, in this context, the ice cap has expanded in response to one of many Little Ice Age Type Events (LIATEs; [Matthews & Briffa, 2005](#)) and secondly, like other upland glacier systems in Iceland, this may not necessarily have been the most recent or classical LIATE of 1600–1900 AD. With these provisos in mind, we refer hereon to the Little Ice Age in its chronologically less specific sense in that the most prominent glacial landforms that define the proglacial forelands, when viewed in the context of dated moraine assemblages on other Icelandic forelands, are indicators of glacier response to climate cooling in the historical period or the Late Holocene.

The glacier forelands were mapped using colour aerial photographs taken by the Icelandic survey company SAMSYN in 2002. After the photographs were orthorectified and mosaicked using Agisoft Photoscan Professional Edition, mapping was undertaken on a coloured ink film overlain on the orthophotograph. The mapping involved the simultaneous interpretation of surface materials and landforms based on ground truth fieldwork in summer 2010 and the viewing of stereoscopic images at the desk top. The orthophotograph processing and contour generation were both performed in ESRI ArcGIS and contours then overlain on the surficial geology and geomorphology. Extensive areas of volcanically related landforms and deposits that lie beyond the glacial materials in the mapped area are depicted by the orthophotograph. A similar approach is taken with the glacier surface, which is represented by the orthophotograph in order to depict ice structures such as crevasses and debris bands. The map overlay containing the base data was manually digitized on a large format Cal-Comp tablet digitizer using MapData vector digitizing software. The digitized vector files for the base data were converted from MapData format into ArcInfo ‘generate’ format for importing into Adobe Illustrator. The map is at a scale of 1:10,526 when printed on an A0 sheet.

3. Surficial geology and glacial geomorphology of Snæfellsjökull

The mapped area ([Main Map](#)) is subdivided into one anthropogenic and nine natural surficial geology units, in addition to bedrock and glacier ice. Bedrock, residuum and paraglacial deposits also comprise the area beyond the historical Little Ice Age limit, as depicted using the orthophotograph.

3.1. Bedrock and residuum

The bedrock of the map area is characterized by the mildly alkali basalts and peralkaline rhyolites, pumice and tephra that have been extruded and erupted from the stratovolcano during several lava flow events ([Figure 2\(b\)](#)). Geomorphologically these materials are organized in sheets, cones and long leveed flow lobes (see orthophotograph area on [Main Map](#)) typical of emplacement on steep mountain slopes or volcano margins, very prominent when viewed from the south coast ([Figure 1](#)). As these volcanic materials are prone to rapid post-depositional weathering, especially at altitudes where freeze-thaw is prevalent, many rock surfaces have been broken down *in situ* to produce a predominantly thin (<50 cm) veneer of residuum. The scale of mapping is not appropriate to the reproduction of the many small patches of residuum in areas of bedrock and vice versa. Hence the bedrock

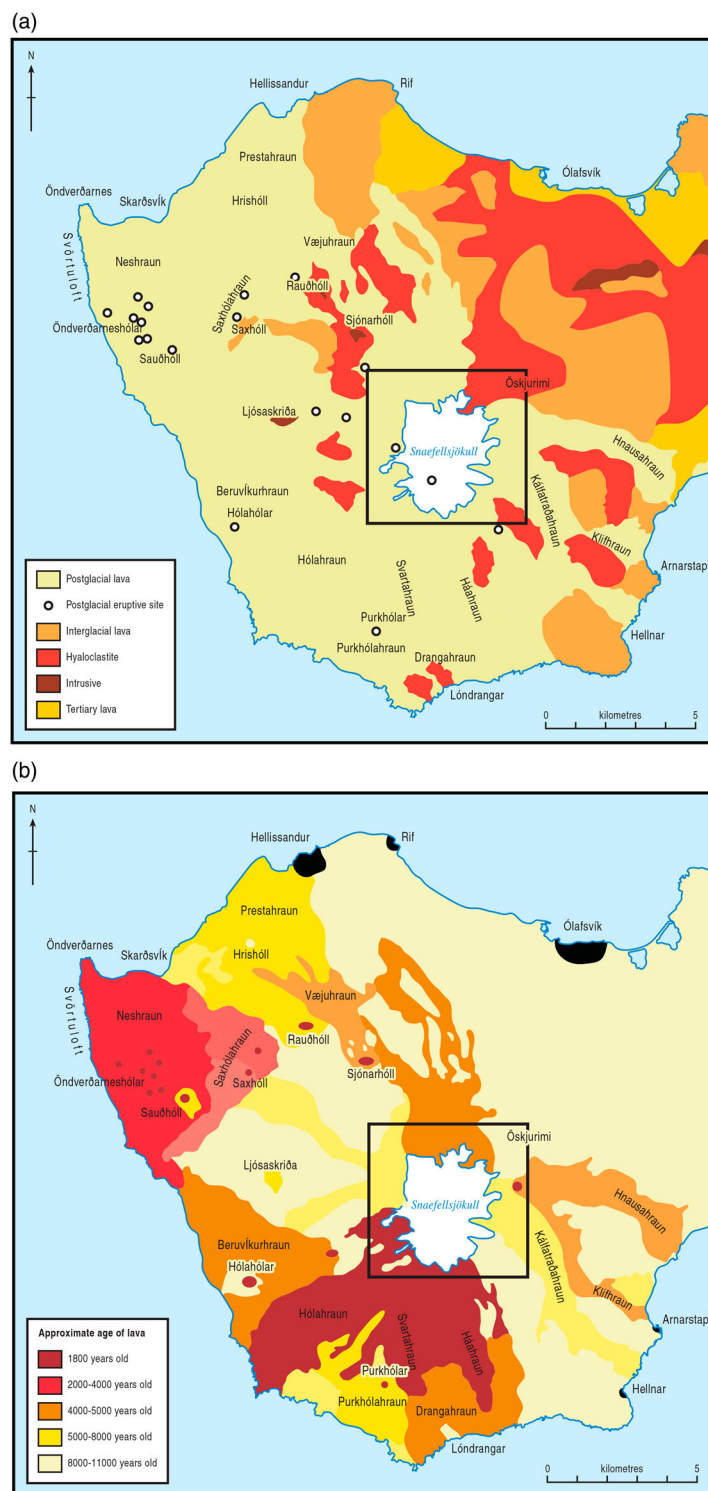


Figure 2. Simplified geology maps of the Snæfellsjökull volcano: (a) principle geological units, from Kokfelt et al. (2009); (b) pattern and ages of lavas, hyaloklastites and intrusives derived from the volcano, from Jóhannesson et al. (1981). Black box shows area covered by Main Map.

and residuum map units are described as containing localized patches of other materials, including old (pre-Little Ice Age) weathered till veneers. The residuum classification in such areas of high relief also includes locally gullied colluvium derived from *in situ* volcanic deposits. At many locations, proglacial and lateral meltwater has incised channels into less resistant lithologies, especially in pumice sheets.

3.2. Till and moraines

The most extensive surface material on the forelands is a predominantly strongly fluted, clast-rich till (Main Map), which is generally less than 2 m thick but locally thickens into recessional push and lateral moraines that are unlikely to contain ice cores (Figure 3). The till, which comprises lower fissile and upper massive

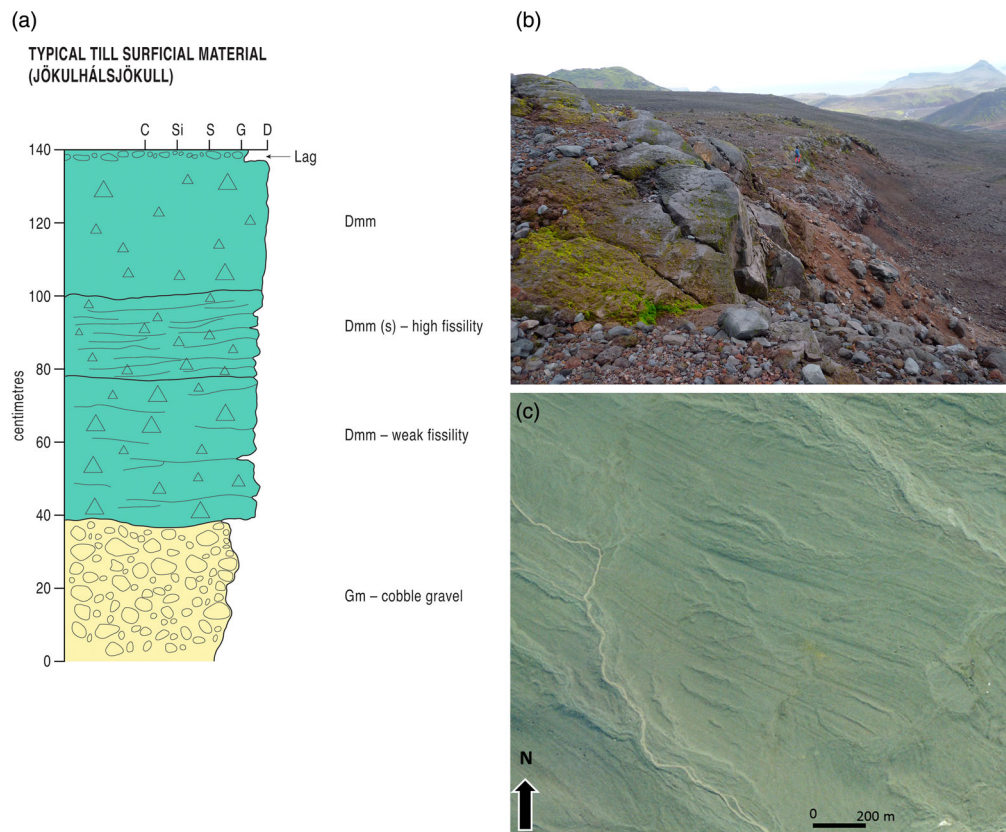


Figure 3. Characteristics of the till and moraine surficial map unit: (a) vertical profile log displaying typical subglacial till characteristics of the till and moraine map unit based upon exposures on the foreland of Jökulhálsjökull (Dmm (s) = massive, matrix-supported diamicton displaying shearing; Gm = massive or structureless gravels); (b) roche moutonnée form on a bedrock step emerging from beneath the thin till cover on the Jökulhálsjökull foreland; (c) aerial photograph (SAMSYN, 2002) extract of the foreland of Hryningsjökull, showing flutings, some with curvilinear plan forms (bottom right), extending to the Little Ice Age hummocky moraine belt.

components (Figure 3(a)), locally thins to reveal heavily striated bedrock protuberances which also display roche moutonnée forms in areas of stepped bedrock profiles (Figure 3(b)). Bedrock steps are locally visible through the thin fluted till cover. Bouldery flutings locally extend down flow from abraded bedrock steps, indicating that

plucking has been effective at the glacier bed, especially where basalt lava overlies less coherent pumice, as occurs on the Jökulhálsjökull foreland, for example. Some flutings on the foreland of Hryningsjökull display a remarkable curvilinear plan form (Figure 3(c)), the origin of which is uncertain but potentially related to late stage

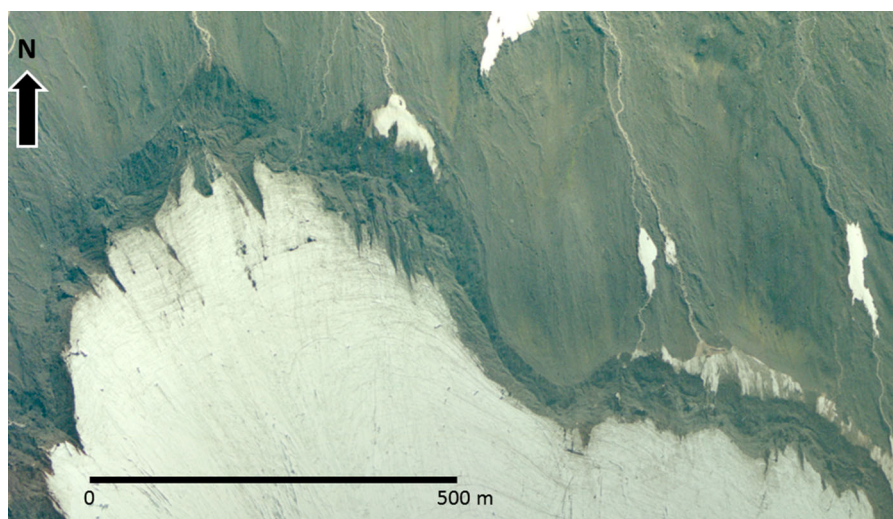


Figure 4. Aerial photograph (SAMSYN, 2002) extract showing the recent ice-cored moraine developing around the margin of Blágilsjökull.

topographic flow constraints on basal ice. Both the bed-rock erosional features and the well-developed flutings indicate that large areas of the outlet glacier beds were temperate and hence subglacial deformation and sliding was in operation at the Little Ice Age maximum (Benn, 1994; Evans, Ewertowski, & Orton, 2015b). The extension of the flutings to the Little Ice Age ice-cored moraine ridge complexes (see section 3.4) constitutes a landform assemblage typical of former polythermal glacier margins identified elsewhere in Icelandic mountain icefields (Evans, 2010, 2011; Evans, Twigg, & Orton, 2010, 2015a). Patches of non-fluted till veneer and occasional boulder spreads ('trimline moraines' *sensu* Ó Cofaigh, Evans, & England, 2003) exist on the distal sides of some ice-cored moraine belts, where they constitute the Little Ice Age maximum limit. These thin deposits are thought to represent the totally de-iced outer margins of the Little Ice Age ice-cored terrain (see Section 3.4). Recent moraine construction is evident in some discontinuous, low amplitude push ridges and ice-cored ridges located less than 100 m from the glacier margins (Figure 4); where ice content is higher this grades into recent ice-cored moraine (see Section 3.4). Localized exposures through the push ridges reveal deformed stratified sediments indicative of recent glacier readvance into proglacial outwash, potentially driven by the mid to late 1990s positive mass balance trends recognized throughout Iceland (e.g. Bennett & Evans, 2012; Bradwell, Dugmore, & Sugden, 2006; Evans & Hiemstra, 2005; Evans, Shand, & Petrie, 2009, 2015b).

3.3. Glacitected pumice moraines

The outermost historical (Little Ice Age) moraines on the forelands of Jökulhálsjökull and Hyrningsjökull are composed entirely of pumice granules. Although these ridges have been heavily dissected by meltwater, they still display an arcuate plan form that parallels the former glacier margin (Main Map; Figure 5). Localized excavations related to mining provide exposures through the deposits and reveal that the pumice is well stratified and locally heavily deformed (Figure 6). Folds and faults indicate that stress was imparted from the west and hence the moraines were constructed by the glacitectonic compression of pre-existing pumice sheets that originally blanketed the eastern slopes of the mountain. The proximal slopes of the pumice moraines are draped by the feather edge of the more recent, basalt boulder-rich hummocky terrain/ice-cored moraine (see Section 3.4), indicating that the glacier snouts have thrust the pumice sheets proglacially and then deposited farther-travelled basalt debris as ice-cored controlled or hummocky moraine and push moraines partially over the pumice moraines (Figure 6). Exposures through the areas of thinner basalt-rich debris reveal that stratified pumice underlies large areas of the

forelands, indicating that the eastern slopes of the volcano were draped by pumice prior to the Little Ice Age advance.

3.4. Ice-cored hummocky terrain and thicker bouldery drift

The Little Ice Age limits on the forelands of the ice cap are demarcated by arcuate assemblages of thick, basalt-rich bouldery drift and ice-cored hummocky terrain (Figure 7; Main Map); on the forelands of Jökulhálsjökull and Hyrningsjökull these lie inside glacitectonized pumice moraines (Figures 5 and 6). Ice cores are obvious where glacier ice is exposed but elsewhere it is assumed based upon buried ice indicators such as large tension cracks, water-filled kettle holes and surface saturation and retrogressive flow slide activity (Figure 7). The hummocky terrain displays numerous discontinuous but substantial linear ridges which could be either individual push features and/or controlled moraine (*sensu* Evans, 2009). This map unit also includes areas of densely spaced push moraines where ice content is uncertain and hence either a controlled moraine or a push moraine origin is possible. Minimal former ice content is evident wherever flutings can be traced through the bouldery surface material, which is classified as 'thicker boulder drift' because it is clearly visibly distinct from the normal fluted till (Figure 7(e)). Interesting features on the proximal side of the ice-cored hummocky terrain on the east Blágilsjökull foreland are large kettle-like depressions into which dry stream beds terminate abruptly, indicating that the depressions acted as sink holes or sumps (Main Map). Meltwater appears to have fed numerous proglacial channels and linear sandar beyond the Little Ice Age limit. These features are further evidence of melting ice cores within the Little Ice Age outer moraine belt. Recent ice-cored moraine, which is being fed by supraglacial controlled debris ridges/englacial debris bands, occurs around the margins of most of the outlet glacier lobes but is best developed around the margin of Blágilsjökull (Figures 4 and 7(f), Main Map). Together with the most recent push moraines (see Section 3.2), this moraine belt possibly marks the position of the mid to late 1990s readvance margin, a feature identified at a range of locations around Iceland (e.g. Bennett & Evans, 2012; Bradwell et al., 2006; Evans et al., 2009, 2015b; Evans & Hiemstra, 2005).

3.5. Overridden moraines

Small areas of the fluted forelands, especially on the Blágilsjökull foreland, are characterized by discontinuous arcuate chains of low amplitude ridges (Figure 8), which are interpreted as overridden moraines (*sensu* Evans, Archer, & Wilson, 1999, 2009, 2015a; Evans & Orton, 2014; Evans & Twigg, 2002; Krüger, 1994).

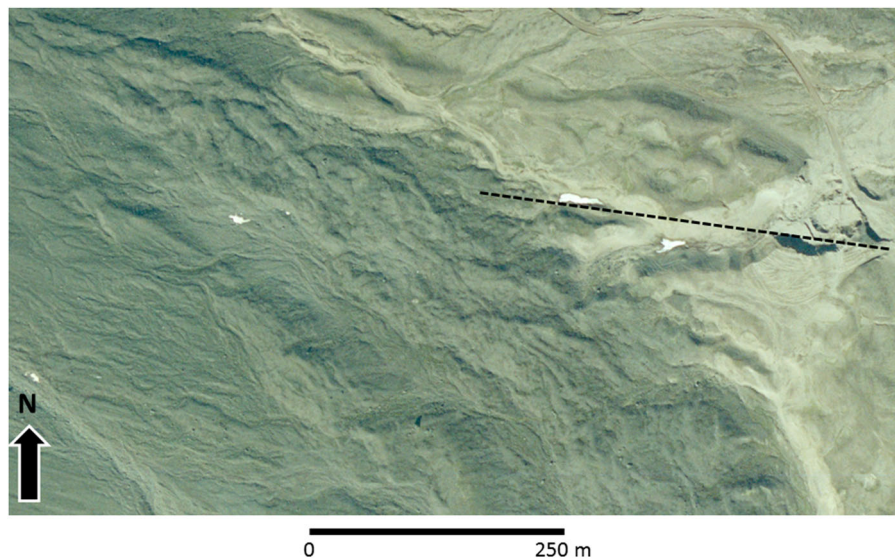


Figure 5. Aerial photograph (SAMSYN, 2002) extract of the northeastern foreland of Hyrningsjökull, showing the outermost historical (Little Ice Age) moraines, with the outer glactectonized pumice ridges visible as a light brown colour and the inner hummocky and ice-cored moraines as darker coloured ridges. A pumice quarry, in which glactectonic structures were logged (see Figure 6(a)), is visible on the far right of the image. Note that meltwater channels have been excavated between, and locally through, moraine ridges. Black broken line shows Figure 6(a) line of cross profile.

Also very prominent on the west side of the Blágilsjökull foreland is a high relief ridge that appears to be a former lateral moraine partially superimposed on to an elongate bedrock promontory. As this feature is locally fluted and draped by recent recessional moraines it is interpreted as an overridden lateral moraine whose main ridge is denoted by the dotted line symbol on the Main Map. Like similar features mapped widely over deglaciated Little Ice Age forelands around Iceland, the overridden moraines of Snæfellsjökull likely date to pre-LIA ice margins overrun during the LIA advance.

3.6. Glacifluvial deposits

Glacifluvial processes have mostly produced linear spreads of outwash sands and gravels confined to narrow valleys, channels and gorges incised into the steep slopes of the volcano (Main Map). Largely discontinuous ribbon sandar also occur on the fluted till surfaces as do occasional esker ridges, especially on the foreland of Blágilsjökull. Debris flow-fed alluvial fans/aprons have also been produced by glacial meltwater on steeper slopes.

3.7. Alluvial fan slackwater deposits

A veneer of fine-grained alluvial fan deposits occurs in the small upland basin that lies between the northwest corner of the Little Ice Age maximum limit of Blágilsjökull and the amphitheatre-like hollow of the east side of the Bárðarkista mountain. These deposits record a short period of drainage damming or slackwater development which back-filled the amphitheatre floor when the glacier margin encroached on the lower slopes of the mountain some 400 m to the northeast. Surface

channels on the sediments document incision by marginal meltwater after the slackwater had drained and these can be traced northwards into incised and terraced outwash that was deposited in and around residuum-covered bedrock highs and pumice mounds at, and just beyond, the Little Ice Age limit.

3.8. Paraglacial deposits

Small areas inside the Little Ice Age limit have been subject to slope processes, whereby glacial sediments and freshly exposed bedrock have been reworked during the period immediately following glacier recession. As these processes are conditioned by deglaciation, they are classified as paraglacial deposits (*sensu* Ballantyne 2002a, 2000b). These deposits largely comprise debris flow fans and screes. Small areas of in situ bedrock too small to depict at the map scale are also included.

3.9. Made ground

Substantial areas of made ground occur on the east side of the icefield, on Jökulháls, where pumice moraines have been quarried. The pumice was transported originally via sluice networks down to the south coast where it was processed for use in the concrete industry from 1937 until sometime in the latter half of the twentieth century. Other small quarries appear to have been excavated for road building material on the F570 mountain track.

4. The volcano-centred ice cap landsystem

The spatial distribution of landforms is consistent throughout the forelands of the various outlet lobes

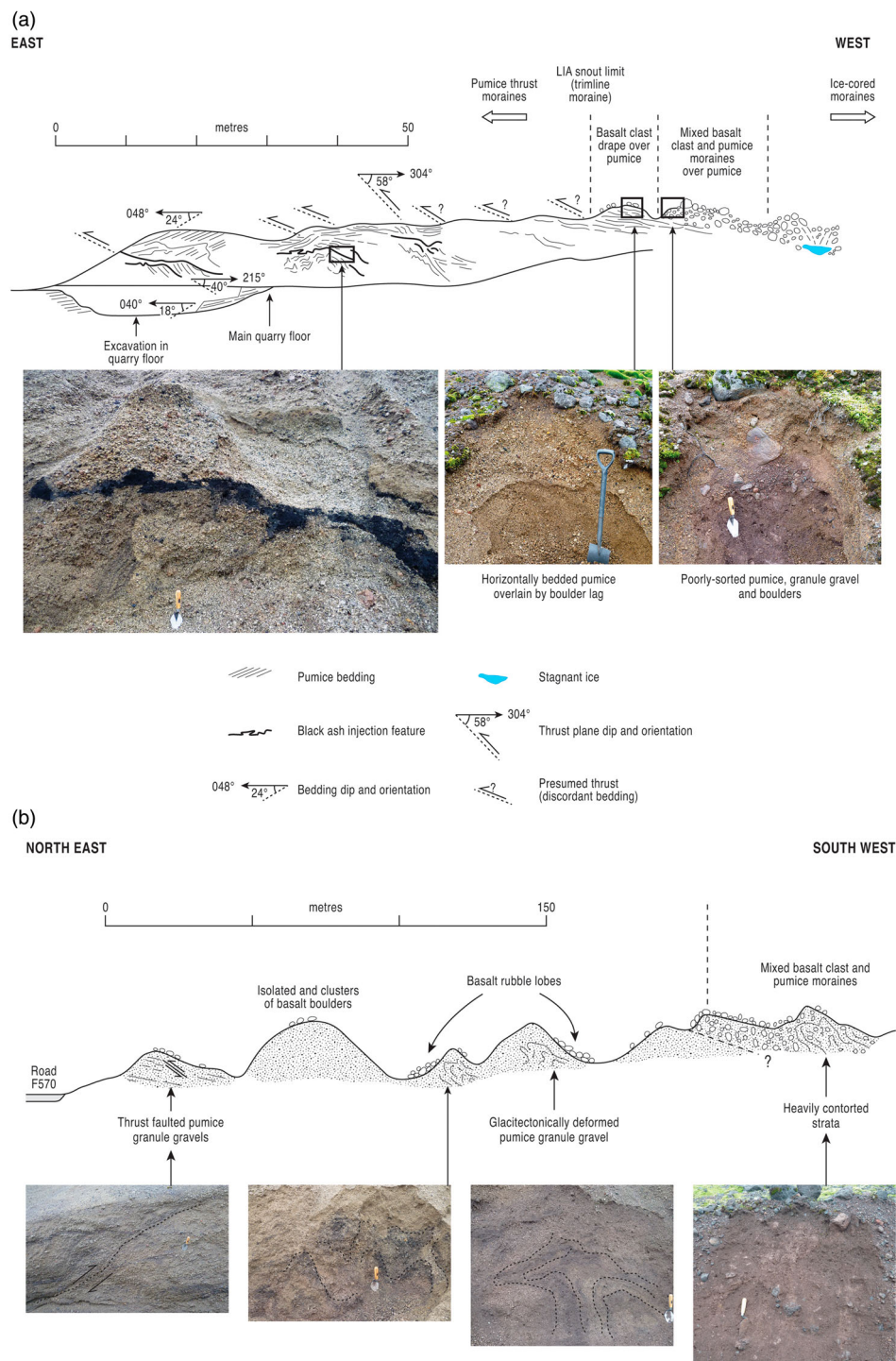


Figure 6. Cross sections through the surficial map units of the outer forelands of Hyrningsjökull (a) and Jökulhálsjökull (b), displaying the morphostratigraphic relationships of the Little Ice Age moraines on the eastern side of the ice cap.

of the Snæfellsjökull ice cap and hence constitutes a landsystem signature for independent volcano-centred ice caps. Specifically this signature comprises extensive areas of ice-cored moraine, developed at the limit of the Little Ice Age readvance and located distal to extensive areas of fluted till and glacially abraded bedrock with occasional eskers. This association has now been widely documented across Iceland, especially in upland settings on the deglaciated forelands of plateau ice-fields, where it is regarded as a landsystem product of former polythermal snout conditions at the Little Ice

Age maximum (e.g. Evans, 2010, 2011; Evans et al., 2010, 2015a). The occurrence of proglacially thrust materials, in this case pumice sheets on the east flanks of the volcano, has been documented also in such polythermal settings, for example, at Eiríksjökull, Iceland (ice-contact fans/aprons; Evans, Ewertowski, & Orton, 2015a) and northwest Ellesmere Island, Arctic Canada (proglacial lake sediments and outwash; Evans, 1989; Evans & England, 1991; Ó Cofaigh et al., 2003), where pre-existing deformable materials are susceptible to thrust block development.

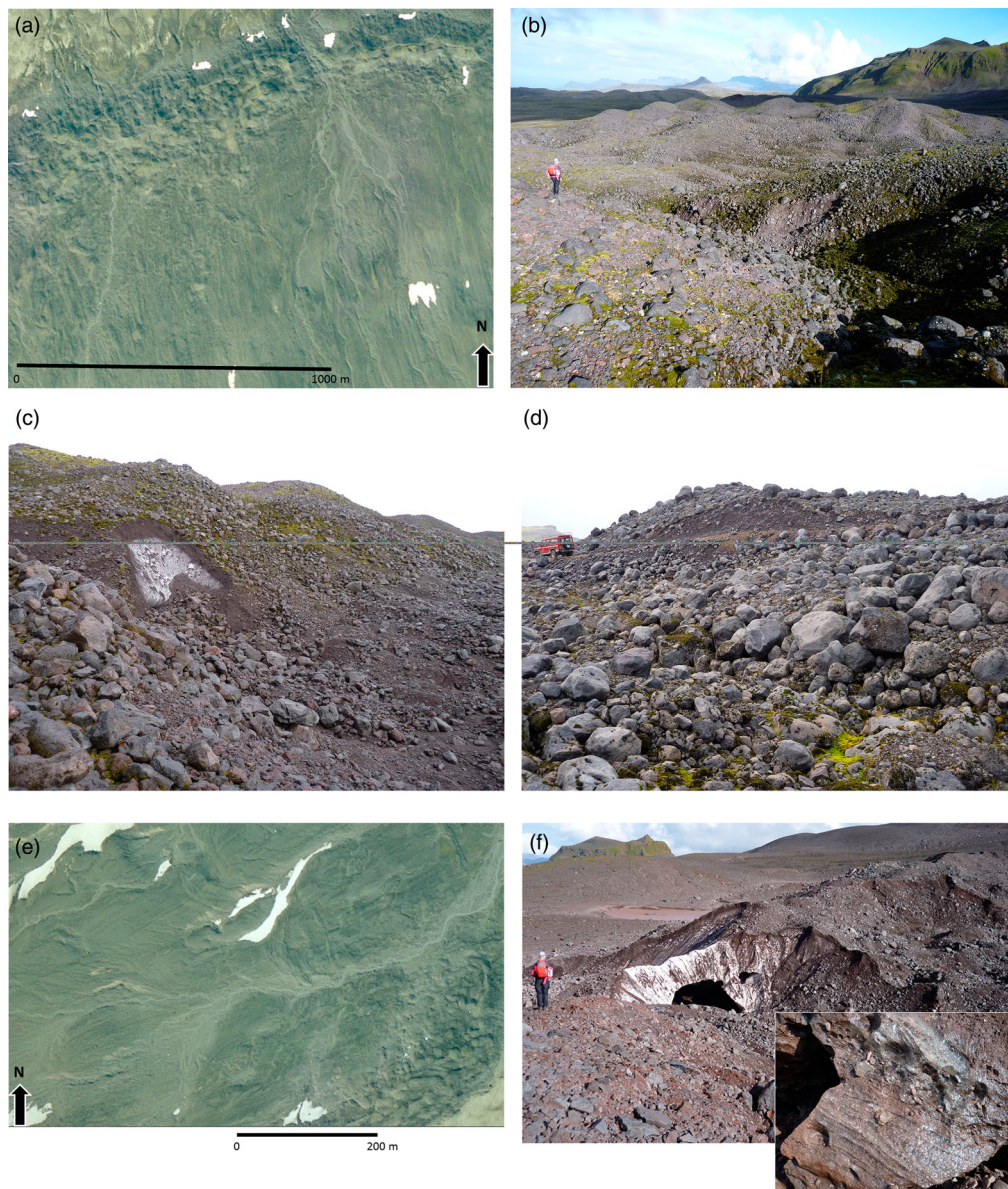


Figure 7. Characteristics of the ice-cored hummocky terrain and thicker bouldery drift: (a) aerial photograph (SAMSYN, 2002) extract showing the Little Ice Age ice-cored moraine arc on the northern edge of the Blágilsjökull foreland. Note that the moraine arc grades southwards into faintly fluted, thicker bouldery drift and then into strongly fluted till. Also visible are narrow corridors of outwash that terminate in sumps on the proximal sides of the ice-cored moraine arc; (b) ground view of the Blágilsjökull ice-cored moraine arc with melt-out pit/sump in the middleground; (c) exposure of glacier ice in the front of the Blágilsjökull ice-cored moraine arc; (d) ground view of the bouldery drift produced by the melt-out of the Blágilsjökull ice-cored moraine arc; (e) aerial photograph (SAMSYN, 2002) extract showing the outer part of the Jökulhálsjökull foreland, inboard of the ice-cored hummocky moraine (visible bottom right), where flutings can be traced through the thicker bouldery drift. Note also the occurrence of some small push moraines in this zone (centre of image); (f) ice-cored moraine (likely dating to the 1990s readvance) near the margin of Blágilsjökull. Inset photograph shows stratified, debris-rich ice indicative of former debris freeze-on at the glacier snout (penknife for scale).

The delivery of bouldery till and glacial debris to the Little Ice Age maximum limit to construct ice-cored and controlled moraine was facilitated by the efficient plucking of vertically jointed basaltic lavas, which in many places stratigraphically overlie less coherent pumice sheets. The horizons identified within the fluted till (Figure 3(a)) are typical of sub-glacially deformed tills identified elsewhere in Icelandic temperate snout settings (e.g. Boulton & Hindmarsh, 1987; Evans, 2000; Evans & Hiemstra, 2005; Evans & Twigg, 2002) and hence the fluted terrain of the

Snæfellsjökull forelands is regarded as diagnostic of a deforming and sliding bed that transported debris to the frozen snout zones, thereby feeding controlled moraine development (*sensu* Evans, 2009) at the Little Ice Age maximum. Linear ridges within the ice-cored hummocky terrain are most likely the manifestation of such controlled moraine but other inset, parallel ridges developed on the proximal and fluted margins of the thicker bouldery drift are more likely to be push moraines constructed in the smaller volumes of englacial debris released by snout melt-out. Hence

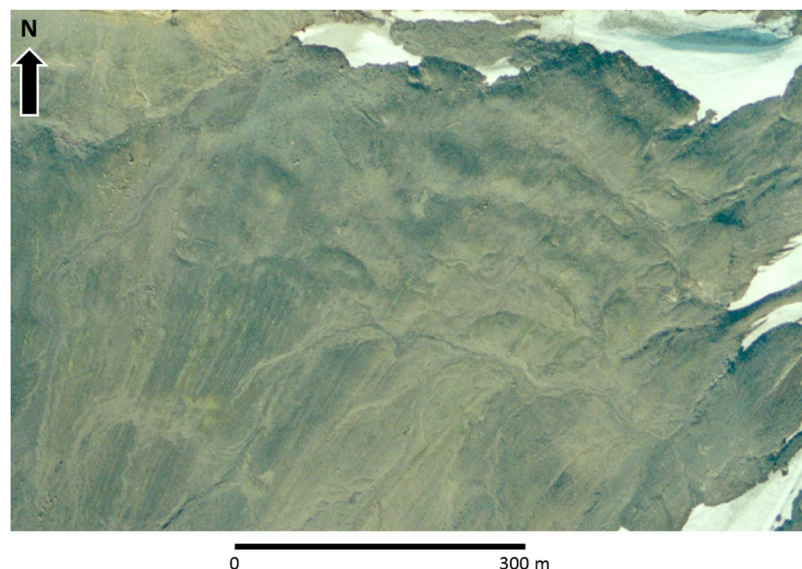


Figure 8. Aerial photograph (SAMSYN, 2002) extract showing overridden and fluted moraines on the northeast part of the Blágilsjökull foreland.

the frozen snout conditions became less proficient in constructing moraine ridges during the early stages of Little Ice Age recession and did not become effective again until the colder climate of the mid to late 1990s, when ice-cored moraine was again constructed at the more restricted snouts.

Conclusions

A 1:10,526 scale map of the Little Ice Age landform-sediment associations on the forelands of the outlet lobes of Snæfellsjökull constitute a landsystem signature for independent volcano-centred ice caps. The landsystem comprises an outer zone of ice-cored moraine in front of which is a locally developed set of proglacially thrust pumice deposits. The ice-cored moraine, documenting former frozen snout conditions, passes proximally into bouldery drift and push moraines and then a large area of flutings and glacially abraded bedrock, indicative of temperate basal ice conditions. This style of landform zonation is widely recognized throughout Iceland on mountain glacier forelands and records former polythermal conditions at the Little Ice Age maximum. Although this landsystem is an exemplar relevant specifically to the Icelandic landscape, it is also more widely relevant to glacierized volcanic terrains globally.

Software

Aerial photographs were orthorectified and mosaicked using Agisoft Photoscan Professional Edition. Orthophoto processing and contour generation were performed in ESRI ArcGIS. Adobe Illustrator was used to draw the map and Adobe Photoshop was used for glacier and background image manipulation.

Disclosure statement

No potential conflict of interest was reported by the authors.

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